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Franz, Martin ; Özcan, Mutlu

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Adhesion of bulk-fill resin composites as core and intraradicular post materials only versus the use of glass-fiber posts in different regions of root dentin

Martin Franz, M Dent Med[a] / Mutlu Özcan, DDS, Dr.med.dent., PhD[b]

[a]*Dentist, University of Zürich, Division of Dental Materials, Center for Dental and Oral Medicine, Clinic for Fixed and Removable Prosthodontics and Dental Materials Science, Zürich, Switzerland*

[b]*Professor, University of Zürich, Division of Dental Materials, Center for Dental and Oral Medicine, Clinic for Fixed and Removable Prosthodontics and Dental Materials Science, Zürich, Switzerland*

Short Title: Adhesion of bulk-fill and fiber posts to root dentin

Correspondence to: *Mutlu Özcan, Prof. Dr. med. dent. PhD, University of Zürich, Dental Materials Unit, Center for Dental and Oral Medicine, Clinic for Fixed and Removable Prosthodontics and Dental Materials Science, Plattenstrasse 11, CH-8032, Zürich, Switzerland Tel: +41-44-634-5600; Fax: +41-44-634-4305. e-mail: mutluozcan@hotmail.com*

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Keywords: Adhesion; Bulk-fill-composite; Dentin; Fiber-reinforced-composite posts; Push-out test; Resin composite.

Introduction

Long-term success of a dental reconstruction on endodontically treated teeth is highly dependent on the amount of structural loss, adhesion and/or retention of the intraradicular posts in the canal, adhesion of the core to the post and preservation of coronal tooth tissue (ferrule effect) [1]. Successful intraradicular post and core restorations eliminate the application of more invasive therapies such as fixed dental prosthesis (FDPs) or implants.

Several post and core materials have been introduced to dentistry during the last few decades. The traditional post material especially for molars and premolars are made of metals posts that are available either in prefabricated forms, which could be applied chairside or could be cast that is fabricated at the dental laboratory. The metal posts retain in the intraradicular dentin due to friction where precision is utmost important [2]. However, due to the high elasticity modulus of such metal posts, over time root fracture has been reported as the most common clinical failure [3,4].

Furthermore, in the anterior region in conjunction with all-ceramic reconstruction materials, metal post and its core may shine through and impairing the optical outcome. As an alternative to metal posts, fiber reinforced composite (FRC) posts have been advocated. FRC post have an elasticity modulus closer to dentin through which the stress, induced on to the roots, is distributed more favourably as opposed to metal posts [5,6]. Such FRC posts are commonly made of carbon, carbon-glass, E- or S-glass fibers embedded in polymer matrix [7]. In order to improve the adhesion and stability of FRC posts, the fibers are embedded in a mixture of polymethylmethacrylate (PMMA) and bisphenol-A-glycidyldimethacrylate (bis-GMA). This chemical matrix creates a semi-interpenetrating polymer network (IPN) that crosslinks the monomers of the post [8,9]. The IPN structure that has a non-reactive surface of the polymer matrix could also adhere to the resin cement that is used to lute the FRC post to the intraradicular dentin [8]. This adaptation and durable adhesion were expected to reduce the risk of reinfection and achieve a homogeneous monobloc structure [10]. As a consequence of light transmission properties, they could be polymerized at a certain depth in the root canal, which also increases their stiffness [11,12]. The use of FRC posts are considered as an integral part of minimal invasive dentistry, since they could be adhesively bonded to the root canal dentin, do not require extensive root canal preparation, preserve the root structure and cause less root fracture [6]. Moreover, translucent FRC posts are also considered optically more favourable in aesthetically demanding regions compared to metal posts [11].

Unfortunately, currently available clinical evidence indicates the loss of retention of the post as the most frequent clinical failure in root canal treated teeth using FRC post and cores [4,13,14]. The major reason for such failures were attributed to the unfavourable c-factor in the root and thereby the shrinkage between the root dentin-cement-FRC complex [15].

Advances in the field of resin-based composites yielded to constant improvement in physical, chemical and mechanical properties of such materials. Shrinkage and shrinkage stresses in particular, that cause voids at the interfaces between the tooth and the resin material, have been the major problems associated with resin composites that could be reduced when applied incrementally not exceeding 2 mm [16,17]. In a post and core application however, incremental application of resin cements is not possible.

Recently, novel chemical formulations of resin composites have been introduced that were modulated in an attempt to reduce the shrinking stress and increase the depth of polymerization [18,19]. The so called bulk-fill resin composites for dental use are distinguished by their viscosity varying from low to medium and allowing clinical application in bulk increments from 2 to 5 mm with high depth of polymerization and low contraction rate [20,21]. The thixotropic properties of such resin composites could be manipulated up to 87% through vibration with the assigned hand pieces. That allows the material to adapt to the dentin walls. In this manner, polymerization stress of 2.99 vol% along with higher light transmittance than with conventional resin-based composites have been reported [21,22]. Furthermore, depending on their chemical compositions, Knoop microhardness values at 4 mm depths varying from 29.7 to 72.4 N/mm^2 on the top and 19.8 to 34 N/mm^2 at the bottom of the bulk material were considered acceptable with a polymerization stress of 2.05 vol% [10,21].

It could be anticipated that such favourable properties of bulk-fill resin composite materials could be an alternative to metal and FRC posts for intraradicular applications that also could eliminate the stresses at dentin-cement-post interfaces and reducing clinical steps significantly. In addition, the use of bulk-fill materials both as a post and core material may have potential advantages to avoid interfacial debonding of the resin cement from the post material itself. Thus, the research question would be whether bulk-fill materials could substitute metal or FRC post and core materials? To the best knowledge of the authors, bulk-fill resin composites have not been tested for post and core indication.

The objectives of this study therefore were to assess the adhesion of bulk-fill resin composites as intraradicular post and core materials only versus the use of metal or FRC posts in different regions of the root dentin in single rooted teeth. The null hypothesis tested were that there would be no significant difference in terms of bond strength between the bulk-fill composites and FRC materials both at the coronal and intraradicular dentin and no difference at different regions of the root.

Materials and Methods

The brands, types, manufacturers and chemical compositions of the materials used in this study are listed in Table 1. Distribution of experimental groups based on the root posts and resin materials and the sequence of experimental procedures are presented in Fig. 1.

Specimen preparation

Human teeth with single root (N=84), were collected and kept in distilled water at 5°C until the experiments. All teeth used in the present study were extracted for reasons unrelated to this project. The inclusion criteria for the teeth were as follows: straight roots, roots of at least 16 mm length, free of fillings, decays or cracks. Written informed consent for research purpose of the extracted teeth was obtained by all donors prior to extraction according to the directives set by the National Federal Council. Ethical guidelines were strictly followed and irreversible anonymization was performed in accordance with State and Federal Law [23-25]. After tissue remnants were removed with a scaler (H6/H7; Hu-Friedy, Chicago, IL), teeth were stored in 0.5% Chloramin T for 2 weeks [26]. The roots of the teeth were embedded until the cement-enamel junction (CEJ) in a polyvinyl chloride (PVC) mould using auto-polymerizing acrylic resin (Scandiquick, Scandia, Hagen, Germany).

The teeth were decoronated at CEJ using a diamond bur (Modell 3241, Precision Vertical Diamond Wire Saw, Well Diamond Wire Saws SA, Le Locle, Switzerland). The roots were mounted in a parallelometer (Type PFG 100, Cendres & Métaux, Biel, Switzerland) and the canals were prepared up to a diameter of 1.35 mm with a working length of 2 mm until the apical foramen using a standard drill (FRC Postec Reamer, Ivoclar Vivadent, Schaan, Liechtenstein). The teeth were randomly divided into seven groups (n=12 per group) having a mean working length of 13.5 mm simulating the endodontic treatment as described elsewhere. Each canal and post was threatened according to the manufacturer's instructions. Each canal was rinsed with 3% sodium hypochlorite, dried and then etched for

15 s with 35 % phosphoric acid (Ultra-Etch, Ultradent, South Jordan, Utah UT, USA). The roots were rinsed with water for 15 s, dried with air blow and paper points (Roeko, Coltene, Altstätten, Switzerland).

Experimental groups

Group TP: In this group, the roots received titanium posts. Initially, the surfaces of titanium posts were conditioned with a metal primer (Alloy Primer, Kuraray Co. Ltd, Tokyo, Japan). The intraradicular dentin was conditioned (ED Primer A + B, Kuraray Co Ltd) with a microbrush (Microbrush X, Microbrush Corp, Grafton, WI, USA), excess was removed with paper points (ROEKO, Coltene, Altstätten, Switzerland). Subsequently, the posts were adhesively cemented using a chemically polymerized MDP containing resin cement (Panavia 21, Kuraray Co. Ltd). The posts were photo polymerized for 40 s using a polywave LED blue light (Bluephase, Ivoclar Vivadent) with an output of 1200 mW/cm^2 and a wavelength of 385-515 nm.

Group SFRC: In this group, FRC posts made of S2-glass (Dentapreg Pinpost, Dentapreg, Brno, Czech Republic) were used. The intraradicular dentin was conditioned as described in group TP. The FRC posts were silanized (Monobond Plus, Ivoclar Vivadent, Schaan, Liechtenstein), adhesively cemented and polymerized in the root as described in group TP. Five pieces of pin posts with a diameter of 0.45 mm were inserted in the canal.

Group EFRC1 (direct): In this group, FRC posts made of E-glass (GC everStick Post 1.2, GC Corporation, Tokyo, Japan) were used, cemented and polymerized after the pretreatment of the dentin as described in Group TP.

Group GFRC: This group received E-glass fibers (Glassix Nordin, Harald Nordin Ltd, Chailly/Montreux, Switzerland) embedded in epoxy resin, cemented and polymerized after the pretreatment of the dentin as described in Group TP.

Group EFRC2 (indirect): In this group, FRC posts made of E-glass (everStick Sticktech Post 1.2, GC Corporation) were used similar to group FRC1 but after try-in in the canal, the FRC post was photo-polymerized out of the canal and then cemented after the pretreatment of the dentin as described in Group TP.

Group BF1: In this group, no post was used but the root canal was filled with a high viscosity bulk-fill resin composite (Surefil SDR, Dentsply, Caulk, York, Pennsylvania, USA). According to the manufacturer's instructions, the dentin surface was scrubbed with a primer (Optibond FL primer, KaVo Kerr Corp, Washington D.C., USA) for 20 s and air-dried. Adhesive resin (OptiBond FL adhesive, KaVo Kerr Corp) was then applied for 15 s, air-dried and photo-polymerized for 10 s. The capsules (shade A2) were warmed up to 68°C using a heating device (CALSET, AdDent, Danbury, CT, USA) before each application. The bulk-fill resin (0.3 g) was subsequently applied in the canal. Photo-polymerization process was identical as described in group SFRC. The material applied in the root canal and the core part of this composite was polymerized separately.

Group BF2: In this group, no post was used but the root canal was filled with a high viscosity bulk-fill resin composite (SonicFill, KaVo Kerr Corp). The capsules (shade A2) were warmed up to 68°C using a heating device (CALSET, AdDent, Danbury, CT, USA). All procedures were similar to group BF1 but here, prior to application the bulk-fill material was initially placed on a vibrating handpiece (Compothixo, KaVo Kerr Corp) that decreased the viscosity of the resin.

The core materials in all groups were applied using a prefabricated silicon mould, positioned at the centre of the coronal dentin (height 5 mm; diameter: 3.6 mm). After conditioning the coronal dentin with an adhesive (Clearfil SE Bond, Kuraray Co Ltd.) and photo-polymerization for 40 s, the core resin material (G-aenial A2, GC Corporation) was applied in groups TP, SFRC, EFRC1, GFRC, EFRC2. In the bulk-fill resin groups (BF1 and BF2), the bulk-fill material itself acted as both root canal fill and core material.

Ageing

The specimens were stored in distilled water (37°C) for 1 h and then subjected to thermocycling (Haake DC 10, Sigma-Aldrich, St. Louis in Missouri, USA) (x5000 cycles, 5˚C to 55˚C, dwelling time 30 s).

Macroshear test

In order to test the adhesion of core material to the coronal dentin, the specimens were mounted in the jig of the Universal Testing Machine (Model Z010 Zwick ROELL, Ulm, Germany). The load was placed to the adhesive interface, as close as possible to the surface of the substrate and the shear force was applied at a crosshead speed of 1 mm/min until failure occurred. The stress-strain curve was analyzed with the software program (TestXpert V11.02, Zwick ROELL, Ulm, Germany).

Push-out test and failure analysis

For the push-out tests, the roots of each specimen were transversally sectioned into slices of 1.8 mm and the retrieved disks classified as coronal (3 mm below CEJ), middle and apical portions.

Push-out test was performed using a cylindrical steel plunger mounted on the Universal Testing Machine (Model Z010, Zwick ROELL). The plunger tip size was selected and positioned to contact only the post, without stressing the surrounding root canal walls. Compressive load was applied at a crosshead speed of 0.5 mm/min until the post segment was dislodged from the root to the apical aspect in the apical-coronal direction.

To evaluate the initial bond strength result (MPa), the maximum load (N) was divided by the area of adhesion surface (mm^2). The adhesion area of each section was computed as the area of the lateral surface of a cone, using the formula:

$SI = \pi(R + r)\, a$

where $\pi = 3.14$, R is the coronal radius, r is the apical radius, a is the apothem, computed using the formula:

$a = [h^2 + (R - r)^2]^{1/2}$

where h is the thickness of the section [12,27] (Figs. 2a-b).

In order to characterize the failure mode, the debonded surfaces were examined using a microscope at magnification x40 (Zeiss MC 80 DX, Jena, Germany) and a digital microscope at x300 (Keyence, Osaka, Japan). Failures were classified as follows, after the shear test between the core material and the coronal dentin: Score 1: Combination of cohesive failure in the core material accompanied with adhesive failure between the post and the core material. Score 2: Complete adhesive failure between the core and post material, Score 3: Adhesive loss of post and core retention at the canal opening with the core material being intact, Score 4: Complete adhesive detachment of the core from the canal opening.

Failures after the push-out test were further classified as follows: Score 1: Cohesive failure in the cement (≥ 30% of the cement surface), Score 2: Adhesive failure between post and cement, Score 3: Adhesive failure between dentin and cement.

Statistical analyses

The data were examined using a statistical software package (SPSS, version 22, SPSS Inc., NY, USA). The means of each group were analyzed using three-way analysis of variance (3-way ANOVA) with push out bond strength (MPa). The dependent variable was the post type (7 levels: TP, SFRC, EFRC1, GFRC, EFRC2, BF1 and BF2). The independent factor was the root level (3 levels: coronal, middle, apical). Multiple comparisons were made by Tukey`s post hoc tests. *P* values less than 0.05 were considered statistically significant in all tests.

Results

Not the root level ($p>0.05$) but the type of core and post material significantly affected the shear and push-out bond strength results ($p<0.001$).

Without the use of a post, when bulk-fill materials were used as core material alone, BF1 (9.2±2.1) and BF2 (9.3±3.1) showed significantly lower bond strength to the cervical dentin ($p<0.05$) compared to those of the other post-core combinations (11.6±2.5 - 19±6.8) (Table 2).

At coronal level (3 mm below CEJ) all FRC post types did not show significant difference in bond strength among each other, being significantly higher than those of TP, BF1 and BF2 (0.57±0.37 - 2.34±1.98). The two bulk-fill materials, BF1 (0.6±0.8) and BF2 (1.3±1.5) did not show significant difference in terms of adhesion to root dentin ($p>0.05$) (Table 3).

At the core level, partial cohesive core fracture with adhesive loss between core and post were more common in Groups SFRC (41.7%) and TP (50%) while BF1 and BF2 showed exclusively adhesive debonding from the dentin surface (Table 2). At the root level, the most favourable failure type (cohesive failure in the cement) was more frequent in Group TP (53%) compared to other groups (3-24%) (Table 3). In groups BF1 and BF2, exclusively complete adhesive failure of the bulk fill material from the intraradicular dentin was observed.

Discussion

This study was undertaken in order to assess the adhesion of bulk-fill resin composites as intraradicular post and core materials only, versus the use of metal or FRC posts in different regions of the root dentin in single rooted teeth. Based on the results of this study, not the root level but the type of core and post material significantly affected the shear and push-out bond strength results. Therefore, the null hypothesis tested could be partially rejected. In this study, the interest of adhesion was both on the coronal and at the root level. When core part of the post debonds from the cervical dentin surface, the overlying reconstruction also fails. Thus, not only the retention but also the adhesion of core material is crucial for successful FDPs. Typically, the cervical dentin, which is basically the deep dentin portion of the tooth, is not always a favourable substrate [28]. Therefore, bonding to dentin was achieved using an etch-and-rinse adhesive approach. The primary bonding mechanism to dentin is primarily diffusion based and depends highly on hybridization or infiltration of resin within the exposed collagen fiber scaffold that is considered to be the golden standard in conditioning dentin [29]. Consequently, the obtained results with all types of post-core combinations were significantly higher than those of bulk-fill materials that were not supported by intraradicular posts. This finding clearly indicates the supporting function of the post to the core material that is in line with a previous study [29]. In this study, bulk-fill materials in high viscosities were used that could be polymerized up to 5 mm in bulk [21,22]. While one was applied with the applicator (BF2), the other one was applied without. Although, the so called compothixo hand piece was meant to decrease the viscosity and thereby increase the wettability, no significant difference was found in terms of their adhesion to the cervical dentin [30]. Thus, the additional benefit of using the applicator could not be verified in this study for the bulk-fill materials tested. Those were basically methacrylate-based resin composites, where BF2 presented slightly higher amount of fillers (69 v%) compared to BF1 (44 v%).

Not only the bond strength values but also the failure types were not favourable for the bulk-fill materials tested. All failure types were adhesive, where complete adhesive detachment of the core was observed from the canal opening. Such failure types would not allow for repair options and would yield to complete debonding of the crown. However, such a failure could be restored by adding a post material after removal of some bulk-fill material from the root dentin. It could still be considered as a favourable failure type as supposed to root fracture, which is the most common clinical failure types in metal post and core restorations [3].

When the adhesion of other post and core combinations are considered on the cervical area, in terms of bond strength, no significant difference was found between the tested systems. Nevertheless, the failure types showed variations where adhesion of the core materials were mostly partial cohesive core fracture with adhesive loss between post and core, which could be considered repairable. In the majority of the cases except for bulk-fill materials however, Score 3 types of failures were observed which indicated the good adhesion of the core to the post material but not to dentin. Hence, in post and core restoration types, adhesion to cervical dentin could be considered as at the weakest part of the assembly. It has to be noted that in this study, no ferrule was created and therefore the experimental set up could be reflected as a worst-case scenario [31]. Additionally, direct and indirect FRC post systems did not show significant difference at the coronal level. These findings are in agreement with a previous study where no significant difference of retention was found between flexible, directly placed fiber-bundle and rigid prefabricated FRC [33]. From clinical perspective, indirect application of the FRC could be considered simpler than the direct ones due to their high stiffness. Yet, both the shear and the push-out tests did not denote significant difference between these posts systems.

The push-out test is considered as a reliable method to measure the bond strengths of posts to intraradicular dentin [32,34]. The unfavourable C-factor, the incomplete polymerization and the induced shrinking stress decreases the bond strength to intraradicular dentin where an increasing C-factor may lead to debonding at interface with dentin [35]. The C-factor in intracoronal cavities varies between a factor of one to five [35] and highly depends on the diameter and the length of the canal [4,6,11].

Previous studies estimated C-factors ranging between 20-30 [36] and 100 [37] where polymerization results in shrinkage forces up to 20 MPa. Based on the results of this study, neither of the post systems exceeded this value when push-out bond strength results are considered. Between all post types FRC posts demonstrated overall significantly better adhesion compared to bulk-fill materials and titanium post (TP). These finding were in fact not surprising for TP due to lack of adhesion between the resin cement and the post surface. However, although bulk-fill materials were based on methacrylate monomers, also significantly lower results were obtained. Although it was postulated that when bulk-fill composites were pre-heated, they would become more flowable [38], this could not guarantee higher degree of conversion after polymerization. It has been previously reported that pre-heated bulk-fill resin composites do not compromise the degree of conversion and even decrease polymerization-induced shrinkage [38]. These findings could be valid for such materials when used as filling materials. However, the results of this study are not in agreement with these statements when the tested bulk-fill materials are used as a post and core material and adhered to intraradicular dentin 3 mm above CEJ.

The exclusive adhesive failures from the root dentin surfaces also support the unfavourable adhesion of such materials to root dentin. Moreover, the diameter, post length, post design, luting cement and the interaction between the interfaces influences the retention of posts considerably [39,40]. With the use of a monoblock bulk-fill resins, even only one interface exists, namely dentin and the resin material, the shrinkage yields to possibly led to detachment of the material from the dentin [10]. In fact, bulk-fill composites present favourable shrinkage properties with shrinkage stress of 2.05% due to the presence of bis-GMA, TEGDMA (5%), EBPDMA and fillers that react to sonic energy which in turn decreases its viscosity [41]. Thus, the other reason for the low adhesion results even in the coronal section could be the insufficient polymerization.

In this study, adhesion results were similar regardless of the regions in the root canal. Although this could be considered to be typical for the TP and bulk-fill materials, the non-significant difference between all FRC posts show similar level of light transmission through the post. Yet, this finding also indicates that longer posts may not be needed. However, due to the low adhesion results, this statement should be further investigated in future studies.

When failure types in the root canal were considered, interestingly, the high incidence of cohesive failures in the luting cement with the use of titanium post clearly indicates that shrinkage of the resin cement and thereby shrinkage stresses was less with this post materials as opposed to all FRC materials. The diameter of the TP post was also slightly higher (1.4 mm coronal, 0.9 apical) than those of the other posts (1.2 to 1.35 mm) that possibly yielded to better frictional forces in the canal.

In order to investigate the adhesion potential of the post and core and cement assemblies, the use of gutta percha was omitted. In fact, in clinical practice the use of this material may even further contaminate and compromise the adhesion of the resin cement in the intraradicular dentin [42]. Thus, the results could be even less favourable when gutta has had been used. However, this could be considered as the limitation of this study and needs to be further investigated whether it has implications on decreased adhesion.

Considering the low core-dentin adhesion, push-out bond strength results and high frequency of adhesive failure types, the bulk-fill resin composites could not be recommended at this stage as post and core materials. Even though they are recommended for bulk applications due to their degree of polymerization at thicknesses exceeding 2 mm. Due to the favourable adhesion results and failure types, at the coronal and root level, core materials should be used in combination with either fiber or titanium posts for durable retention of the single crowns of FDPs, providing that the adhesion results are still not ideal in the root canal when compared to the adhesion results in conventional filling indications.

Conclusions

From this study, the following could be concluded:

1. The adhesion of the core materials to the coronal dentin was the least favourable with bulk-fill materials due to low bond strength and exclusively adhesive failures, as opposed to the post and core combinations indicating the retentive function of the post underlying the core material.
2. FRC posts of all kinds tested demonstrated significantly higher bond strength to intraradicular canal compared to titanium post and bulk-fill materials at all root levels.
3. Failure types at the core level were more favourable for S-glass pin posts and titanium post with mainly partial cohesive core fractures with adhesive loss between core and post.
4. At the root level, the cohesive failure in the cement was more frequent with the use of titanium post.

Clinical Relevance

Considering the low core-dentin adhesion, push-out bond strength results and high frequency of adhesive failure types, bulk-fill resin composites could not be recommended for clinical use. Due to favourable adhesion and failure types, at the coronal level and root level, core materials should be used in combination with either fiber or titanium post.

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Conflict of interest

The authors did not have any commercial interest in any of the materials used in this study.

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Captions to tables and figures:

Tables:

Table 1. The brands, batch numbers, manufacturers, types, and chemical compositions of the main materials used in this study. Ba-Al-B-Si: barium-aluminium borosilicate, Ba-B-Si: barium-boron-silica, Ba-St-Al-F-Si: barium-strontium-alumina-fluorine-silica, BDDMA: 1,4-butylene dimethacrylate, Bis-GMA: bisphenol-A diglycidylmethacrylate, CO: Camphorquinone, DMA: apliphatic dimethacrylate, DMAEMA: 2-dimethylaminoethyl methacrylate, EBPDMA: ethoxylated Bis-GMA, GPDM: glycerol phosphate dimethacrylate, HEMA: 2-hydroxyethyl methacrylate, MDP: methacryloxydodecyl pyridinium, 10-MDP: 10-methacryloyloxydecyl dihydrogen phosphate, MMA: methyl methacrylate, MMEP: mono-2-methacryloxylethyphtalate, 5-NMSA: n-methacryloxyl-5-aminosalicylic acid, PMMA: polymethyl methacrylate, TPBSS: sodium 2,4,6-triisopropylbenzenesulfinate, TEGDMA: triethylene glycol dimethacrylate, UDMA: urethane dimethacrylate, VBATDT: 6(-4-vinylbenzyl-npropyl) amino-1,3,5 triazine-2,4-dithione.

Table 2. The mean shear bond strength of the core materials to the coronal dentin (MPa ± standard deviations), minimum and maximal values (CI 95%) and distribution and frequency of failure types per experimental group analyzed after bond strength test with the representative photos from failure types: Score 1: Combination of cohesive failure in the core material accompanied with adhesive failure between the post and the core material. Score 2: Complete adhesive failure between the core and post material, Score 3: Adhesive loss of post and core retention at the canal opening with the core material being intact, Score 4: Complete adhesive detachment of the core from the canal opening. The same superscript lowercase letters in the same column indicate no significant differences ($p<0.05$). For test group descriptions see Fig. 1.

Table 3. The mean overall, and regional (coronal, middle, apical) push-out bond strength of the post materials to the root dentin (MPa ± standard deviations), minimum and maximal values (CI 95%) and distribution and frequency of failure types per experimental group analyzed after push-out test with the representative photos from failure types: Score 1: Cohesive failure in the cement (≥ 30% of the cement surface), Score 2: Adhesive failure between post and cement, Score 3: Adhesive failure between dentin and cement. The same superscript lowercase letters in the same column indicate no significant differences ($p<0.05$). For test group descriptions see Fig. 1.

Figures:

Fig. 1. Flow-chart showing experimental sequence and allocation of groups.

Figs. 2a-b a) Schematic drawing of the conic section of a specimen, **b)** Calculation of the generatrix [12].

Tables:

Brand	Manufacturer	Type / Chemical Composition
Flat head T Titanium (occlusal: ø: 1.4 mm; apex: ø: 0.9 mm) (Batch no: 0000237284)	Cendres + Métaux Ltd, Biel, Switzerland	Pure titanium, conical shape, Size 3
Dentapreg Pinpost (ø: 0.45 mm) (Batch no: PP45_01-022014)	Dentapreg, Brno, Czech Republic	Aerospace-grade S-2 glass fibers (60 wt%), MMA
GC everStick (ø: 1.2mm) (Batch no: 140813A)	Stick Tech, GC Corporation	E-glass fiber (60 wt%), PMMA, bis-GMA, TEGDMA, DMAEMA, camphoroquinone
everStick Sticktech (ø: 1.2 mm) (Batch no: U8601 951319)	Stick Tech, GC Corporation, Tokyo, Japan	E-glass fiber (60 wt%), PMMA, bis-GMA, TEGDMA, DMAEMA, camphoroquinone
Glassix Nordin (ø: 1.35 mm) (Batch no: 216565)	Harald Nordin Ltd, Chailly, Montreux, Switzerland	E-glass fiber (65 wt%), epoxy resin
Surefil SDR (Shade A2) (Batch no: 140718)	Dentsply, Caulk, York, Pennsylvania PA, USA	Bulk Fill composite (polymerization depth: 4 mm; shrinkage stress: 2.99%), Monomer: Modified UDMA, TEGDMA, EBPDMA Fillers: Ba-St-Al-F-Si-glass (68 wt%; 44 vol%)
SonicFill (Shade A2) (Batch no: 35184)	KaVo Kerr Corp, Washington D.C., USA	Bulk Fill composite (polymerization depth: 5 mm / shrinkage stress: 2.05%), Monomer: bis-GMA, TEGDMA (5%), EBPDMA Fillers: silica, Ba-glass (83.5 wt%; 69 vol%)
G-aenial anterior (Shade A2) (Batch no:09122111)	GC Corporation	Resin composite (polymerization depth: 2.5 mm; shrinkage stress: 2.4%), Monomer: Methacrylate, UDMA Fillers: prepolymerized fillers, silica, strontium and lanthanoid fluoride, silica, fumed silica (81wt%)
Ultra-etch (Batch no: 8561)	Ultradent, South Jordan, Utah UT, USA	35% phosphoric acid, water
Optibond FL, primer (Batch no: 5534310)	KaVo Kerr Corp, Washington D.C., USA	2-HEMA, GPDM, MMEP, ethanol, water, initiators
Optibond FL, adhesive (Batch no: 5594053)	KaVo Kerr Corp	bis-GMA, HEMA, GPDM, Ba-Al-B-Si glass, disodium hexafluorosilicate, fumed silica (48 wt%)
Monobond Plus (Batch no: W32661)	Ivoclar Vivadent, Schaan, Liechtenstein	Alcohol solution of silane methacrylate, phosphoric acid methacrylate and sulphide methacrylate
Alloy Primer (Batch no: 00284)	Kuraray Co Ltd, Tokyo, Japan	10-MDP, VBATDT, acetone
ED Primer (Batch no00571A)	Kuraray Co Ltd	Liquid A: 2-HEMA, MDP, 5-NMSA, water, accelerators Liquid B: 5-NMSA, water, catalysts, accelerators

Panavia 21 (Batch no: 00443A 00221 B)	Kuraray Co Ltd	Self-etching dual-cure resin cement, Catalyst: 10-MDP Paste A: BDDMA, hydrophobic DMA, hydrophilic DMA, silanated silica filler, silanated colloidal silica, catalysts, initiators Paste B: benzoylperoxide, TPBSS, N-diethanol p-toluidine, sodium fluoride, hydrophobic DMA, hydrophilic DMA, Ba-B-Si glass, catalysts, accelerators, silica containing composite (70.8 wt%)

Table 1. The brands, batch numbers, manufacturers, types and chemical compositions of the main materials used in this study. Ba-Al-B-Si: barium-aluminium borosilicate, Ba-B-Si: barium-boron-silica, Ba-St-Al-F-Si: barium-strontium-alumina-fluorine-silica, BDDMA: 1,4-butylene dimethacrylate, Bis-GMA: bisphenol-A diglycidylmethacrylate, CO: Camphorquinone, DMA: apliphatic dimethacrylate, DMAEMA: 2-dimethylaminoethyl methacrylate, EBPDMA: ethoxylated Bis-GMA, GPDM: glycerol phosphate dimethacrylate, HEMA: 2-hydroxyethyl methacrylate, MDP: methacryloxydodecyl pyridinium, 10-MDP: 10-methacryloyloxydecyl dihydrogen phosphate, MMA: methyl methacrylate, MMEP: mono-2-methacryloxylethyphtalate, 5-NMSA: n-methacryloxyl-5-aminosalicylic acid, PMMA: polymethyl methacrylate, TPBSS: sodium 2,4,6-triisopropylbenzenesulfinate, TEGDMA: triethylene glycol dimethacrylate, UDMA: urethane dimethacrylate, VBATDT: 6(-4-vinylbenzyl-npropyl) amino-1,3,5 triazine-2,4-dithione.

Groups	Number of specimen	Shear bond strength of core to coronal dentin (Mean ± SD)	*Min-Max (95% CI)*	Failure type distribution n (%)			
				Score 1 	**Score 2** 	**Score 3** 	**Score 4** 
TP	12	18.96±6.79[a,b]	7.45-33.90 (15.11-22.80)	6 (50)	1 (8.3)	5 (41.7)	0 (0)
SFRC	12	15.10±2.88[a]	10.11-20.37 (13.47-16.73)	5 (41.7)	0 (0)	7 (58.3)	0 (0)
EFRC1	12	13.26±1.59[a]	10.59-15.66 (12.36-14.16)	2 (16.7)	0 (0)	7 (58.3)	3 (25)
GFRC	12	15.10±2.63[a]	11.01-20.62 (13.61-16.59)	3 (25)	0 (0)	5 (41.7)	4 (33.3)
EFRC2	12	11.56±2.48[a,c]	8.44-16.54 (10.16-12.96)	3 (25)	0 (0)	8 (66.7)	1 (8.3)
BF1	12	9.20±2.06[b,d]	5.84-13.03 (8.03-10.37)	0 (0)	0 (0)	0 (0)	12 (100)
BF2	12	9.31±3.13[b,d]	5.41-18.05 (7.54-11.08)	0 (0)	0 (0)	0 (0)	12 (100)

Table 2. The mean shear bond strength of the core materials to the coronal dentin (MPa ± standard deviations), minimum and maximal values (CI 95%) and distribution and frequency of failure types per experimental group analyzed after bond strength test: Score 1: Combination of cohesive failure in the core material accompanied with adhesive failure between the post and the core material with the representative photos from failure types. Score 2: Complete adhesive failure between the core and post material, Score 3: Adhesive loss of post and core retention at the canal opening with the core material being intact, Score 4: Complete adhesive detachment of the core from the canal opening. The same superscript lowercase letters in the same column indicate no significant differences ($p<0.05$). For test group descriptions see Fig. 1.

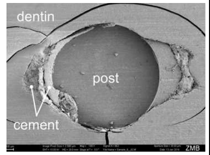
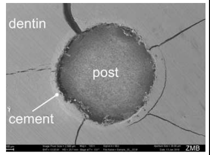
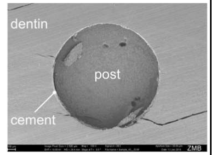
Groups	Number of specimens tested in coronal/ middle/apical regions	Overall push-out bond strength (Mean ± SD)	Coronal (Mean ± SD)	Middle (Mean ± SD)	Apical (Mean ± SD)	*Min-Max (95% CI)*	Failure type distribution n (%)		
							Score 1 	**Score 2** 	**Score 3** 
TP	12/12/12	1.38±0.94[b]	1.80±1.06	1.30±0.81	1.03±0.74	0.00-3.86 (1.07-1.68)	19 (53)	0 (0)	17 (47)
SFRC	11/12/10	5.09±2.26[a]	4.66±2.46	4.88±1.64	5.83±2.76	1.70-10.95 (4.32-5.87)	8 (24)	7 (21)	18 (55)
EFRC1	12/11/10	4.76±2.65[a]	2.87±1.24	4.82±1.93	5.96±3.49	1.08-14.85 (3.87-5.65)	1 (3)	9 (26)	24 (71)
GFRC	12/12/11	4.76±1.88[a]	4.73±1.29	5.02±1.80	4.50±2.41	0.77-8.45 (4.13-5.38)	0 (0)	35 (100)	0 (0)
EFRC2	12/12/12	3.47±1.81[a]	2.76±1.05	3.79±1.92	3.85±2.08	1.06-8.05 (2.88-4.06)	0 (0)	3 (8)	33 (92)
BF1	12/11/11	0.62±0.71[b]	0.57±0.37	0.69±0.94	0.60±0.72	0.00-3.72 (0.38-0.86)	0 (0)	0 (0)	34 (100)
BF2	12/12/12	1.32±1.53[b]	2.34±1.98	1.12±0.97	0.50±0.67	0.00-7.16 (0.82-1.82)	0 (0)	0 (0)	36 (100)

Table 3. The mean overall, and regional (coronal, middle, apical) push-out bond strength of the post materials to the root dentin (MPa ± standard deviations), minimum and maximal values (CI 95%) and distribution and frequency of failure types per experimental group analyzed after push-out test with the representative photos from failure types: Score 1: Cohesive failure in the cement (≥ 30% of the cement surface), Score 2: Adhesive failure between post and cement, Score 3: Adhesive failure between dentin and cement. The same superscript lowercase letters in the same column indicate no significant differences ($p<0.05$). For test group descriptions see Fig. 1.

Figures:

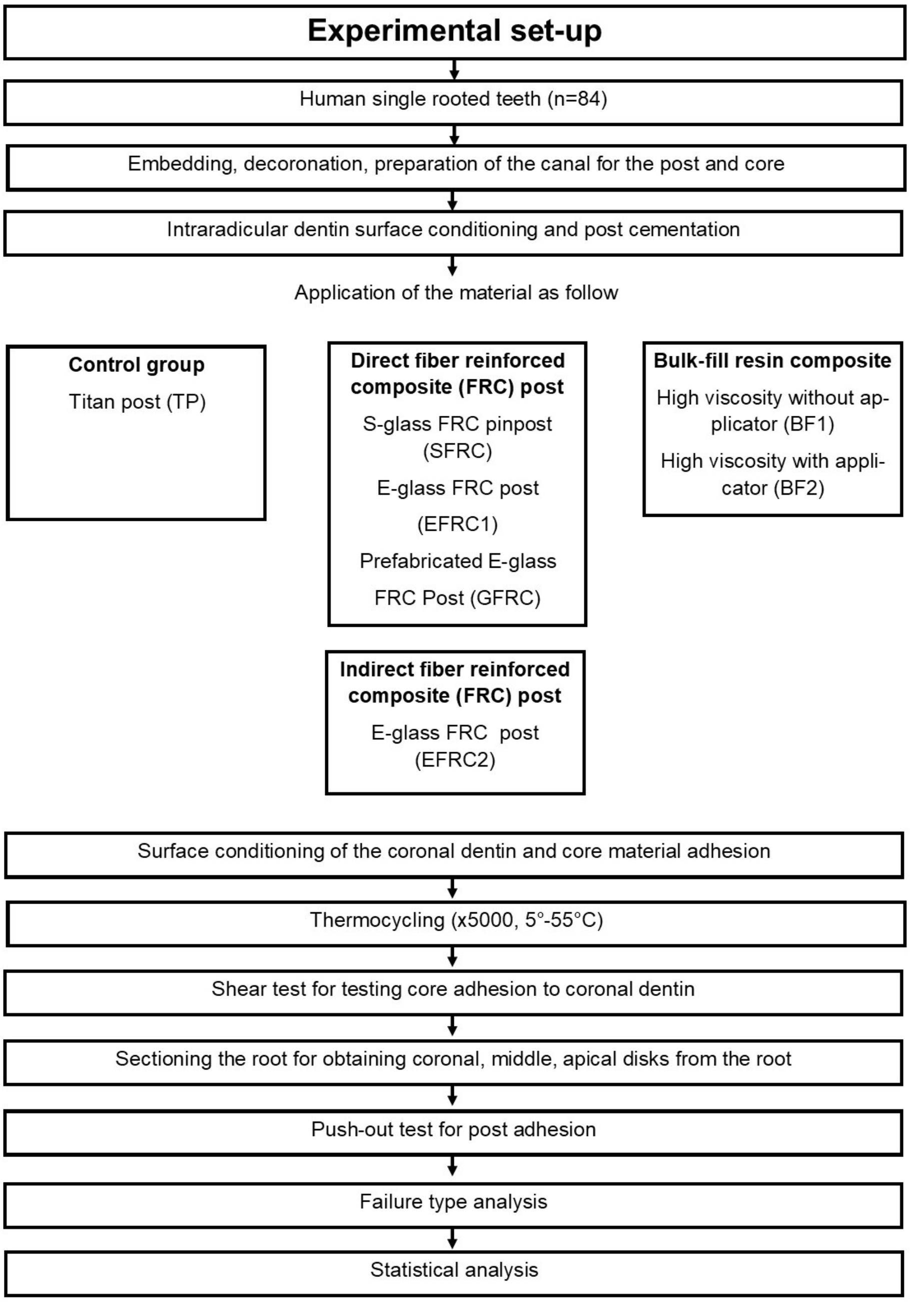
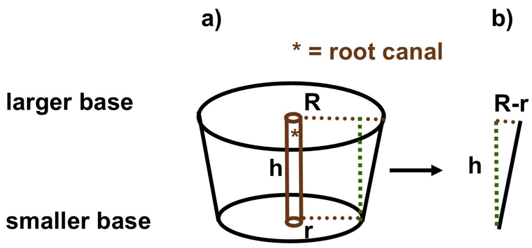


Fig. 1. Flow-chart showing experimental sequence and allocation of groups.



$$Sl = \pi \, (R + r) \, [h^2 + (R - r)^2]^{1/2}$$

Figs. 2a-b a) Schematic drawing of the conic section of a specimen, **b)** Calculation of the generatrix [12].